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RESEARCH ON PREDICTION TECHNIQUES FOR THE TIME DEPENDENCE OF SO--ETC(U)

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RESEARCH ON PREDICTION TECHNIQUES FOR THE TIME DEPENDENCE OF SOLAR PARTICLE EVENTS AND GEOMAGNETIC ACTIVITY FROM RESULTS OF SYNOPTIC ANALYSIS OF SOLAR AND INTERPLANETARY PARTICLE, PLASMA AND FIELD OBSERVATIONS

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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>A total of eight scientific techniques have been investigated as an aid for prediction of solar energetic particle events and geomagnetic storms: (1) Synoptic analysis of interplanetary data; (2) H <sub>α</sub> synoptic charts of low coronal magnetic structure; (3) Solar wind mapping of high coronal emission longitude of solar wind plasma and large-scale interplanetary magnetic field lines; (4) Analysis of energetic particle propagation; (5) Intercomparison of data from separated spacecraft; (6) Charts of solar optical, radio and x-ray activity; |   |   |  |

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(7) Synthesis of solar and interplanetary data; and (8) Integration of interplanetary radio scintillation observations. The progress made in these techniques and their applications is reviewed and evaluated. Based on these results, new recommendations are offered for prediction and operational forecasting.

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## 1. INTRODUCTION

In our original proposal (November, 1974) for solar-terrestrial prediction research, we outlined eight scientific techniques which we intended to apply to the problem of predicting solar energetic particle events and geomagnetic storms. The development of these techniques by ourselves and collaborators has been documented by 25 publications supported by this effort which appeared in journals and conference proceedings 1976-1980. Section 2 summarizes our progress in these techniques. The related publications, the personnel involved, and our participation in scientific meetings are given in Section 3.

Under a sub-contract to the McMath-Hulbert Observatory of the University of Michigan which began in 1978, Professor Helen W. Dodson Prince, Miss E. Ruth Hedeman and Professor Orren C. Mohler carried out a series of systematic analyses relevant to the prediction of solar-terrestrial disturbances. The analyses utilized further developments of the techniques outlined in Section 2. The reports stemming from the sub-contract which concluded October 1979 are summarized in Section 4.

The accumulated scientific results from all the work mentioned above facilitated the compilation of Findings and Recommendations concerning the prediction of solar flare particle events. The compilation was incorporated verbatim into the Proceedings of the International Solar Terrestrial Predictions Workshop (Working Group B3, G. A. Paulikas, Chairman), which met in Boulder, Colorado, April 1979. The Findings and Recommendations are presented in full in Section 5.

## 2. TECHNIQUE DEVELOPMENT

We review below our progress in using the eight scientific techniques originally proposed for prediction applications. For brevity we list the 26 publications in which the techniques were presented and validated in Section 3.1 and cite them by number only in this Section.

2.1 Synoptic Analysis. The comparison of the effects on the interplanetary medium during successive recurrences of the same active region (or coronal structure), has allowed us to isolate causal relationships and evolutionary characteristics. Early in Solar Cycle 20 (1964-1965), when flare activity was low, we

were able to establish that there were recurrent "escape regions" on the sun (21), i.e., longitude regions  $\geq 60^\circ$  wide where  $\sim 1$  MeV protons preferentially were injected even though the most likely acceleration site for the particles was often different on succeeding rotations. Interestingly, these escape regions were not closely correlated with the sources of recurrent solar wind streams observed during the same epoch (11). During the decline of Solar Cycle 20 (1972-1976), almost 70% of the time interplanetary fluxes of 1-5 MeV protons were quasi-steady, spatial events, and of these, about 1/3 were not associated with solar wind streams (3). Indeed, we found a series of recurrent proton flux minima which were associated with a growing solar wind stream (20), and numerous examples of independent evolution of spatial proton events and recurrent stream evolution could be found in this period (1).

2.2 H $\alpha$  Synoptic Charts. We had decided in the early 1970's that the H $\alpha$  absorption features in the low corona served as long-term indicators of the boundaries of the large-scale low coronal structure which influenced the escape of energetic particles and solar wind. This effort supported the ensuing years of demanding work by P. S. McIntosh of NOAA/SEL and a group of dedicated solar cartographers which resulted in the publication of the Annotated Atlas of H $\alpha$  Synoptic Charts (8) which mapped the solar corona for each of the 130 Solar Rotations 1487-1616 during ten years of Solar Cycle 20 (1964-1974). While these charts are now coming into use by solar physicists, we have used them to identify the boundaries of source regions of energetic particles with those of large-scale regions of magnetic polarity in the sun (2, 11, 15), and to confirm that sources of recurrent solar wind streams often (but not always), lie above such "open" magnetic regions (10, 11, 12).

2.3 Solar Wind Mapping. Under a previous Air Force contract, we had validated the constant radial velocity approximation for estimating the source longitude of a given sample of solar wind plasma and hence the magnetic field lines "frozen" into it. During this work effort, this has become our basic technique for ordering interplanetary data according to the coronal source location of interplanetary plasma and magnetic field lines. We verified that the evolution of the boundaries of equatorial coronal holes (observed in soft x-rays by Skylab) corresponded to that of solar wind streams (12), we deduced the three-dimensional high coronal structure of a solar wind source (13), and we demonstrated that the latitude gradients in solar wind streams corresponded to latitude variations in

$H_{\alpha}$  features in the low corona (10). We proposed a method for the incorporation of real-time solar wind data into particle event prediction algorithms in order to anticipate flux variations due to changes in coronal connection longitude (17, 18).

2.4 Collimated Convection Propagation Analysis. The concept of the confinement of low energy protons to moving large-scale interplanetary field lines was elucidated and verified by a number of observational analyses (15, 19, 20, 22). The latest in this series of papers (25) establishes that the mean-free-path for transverse diffusion of 2-4 MeV protons is too small to be measured, and places an upper bound on the ratio of transverse to parallel mean-free-paths  $\lambda_{\perp}/\lambda_{\parallel} < 10^{-2}$ .

2.5 Multiple Spacecraft Analysis. The combination of the techniques of labelling interplanetary field lines by their high coronal foot-point and propagation analysis with negligible transverse transport (other than the  $\underline{E} \times \underline{B}$  motion of the field lines themselves), allows one to compare particle fluxes at separated spacecraft as a function of coronal emission longitude (15, 16, 19, 20). Detailed analysis of large events using up to five separated spacecraft (5, 14) verifies that there are preferred "escape regions" remote from the flare site even for very large flares like April 10, 1969. The technique has also been applied to Pioneer 10 and 11 measurements and shows that the histories of  $> 10$  MeV solar proton events are even more drastically distorted by connection longitude shifts in the outer heliosphere than they are at 1 AU (19). Relativistic Jovian electrons observed from earth to beyond Jupiter independently confirm the strong effects of solar wind structure on particle propagation beyond 1 AU (2,4).

2.6 Solar Activity Charts. These charts, one per solar rotation, summarize solar flare activity in optical, radio and x-ray wave lengths. A detailed set for the Skylab period (Carrington Rotations 1600-1611) were prepared and published (7), and special charts have been constructed for detailed analysis of flare events in 1967, 1969, 1972-6 and 1977 (5, 14, 25). A further development of the charts was made by the McMath-Hulbert group and incorporated into their solar-terrestrial analysis, as will be described in Section 4.

2.7 Synthesis of Solar and Interplanetary Data. We have already mentioned several analyses which established large-scale relationships between coronal magnetic structure and both solar wind streams and energetic particle populations



(1, 5, 10, 11, 12, 13, 14, 15, 19, 20, 21). By this technique, we were also successful in identifying the emission sites of the recently discovered "Z-rich" solar events (23, 25). These small solar particle events display progressive enhancements of ion overabundances from He through CNO to Fe. Using solar wind mapping of particle fluxes and solar wind plasma, combined with specially constructed Solar Activity Charts, we demonstrated that during 1972-1976 these over-abundant ions probably were produced in the pre-flare heating of small active regions which exhibited steady sub-flare activity on the sun's western hemisphere. In another application, we constructed an atlas of soft x-ray loop structure photographed by Skylab April 1973-February 1974 (6), and by comparing with multi-spacecraft mapped flare-associated 2-4 MeV proton fluxes, we demonstrated that a possible mode of coronal transport of these particles is via high-lying loops from the flare site to open field lines in a distant ( $> 15^\circ$ ) escape region (16). Applications of the synthesis techniques to prediction (17, 18) are discussed in detail in Section 5.

2.8 Integration of Interplanetary Radio Scintillation Observations. After applying the theory of IPS response which we developed (9) to an extended set of synoptic observations from the University of Iowa COCOA-Cross Array at Clark Lake Radio Observatory, we concluded that the dominant response at low observing frequencies (38 MHz) was due to plasma density enhancements in the leading edge of high speed streams. The IPS signature was clearest when the disturbance was  $< 0.3$  AU from the earth, providing a useful prediction with a  $< 24$ -hour lead time of geomagnetic disturbances and changes in energetic particle fluxes, but was not directly applicable (at present instrumental sensitivities) to our longer term synoptic analyses. The observational program was supported independently of this effort.

### 3. PUBLICATIONS, PERSONNEL AND ACTIVITIES

#### 3.1 Publications Resulting from Work Under this Contract

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16. Roelof, E. C., Solar energetic particles: From the corona to the magnetotail, in Quantitative Modelling of Magnetospheric Processes, ed. W. P. Olson, Geophysical Monograph 21, American Geophysical Union (Washington, D. C.), 220, 1979.

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### 3.2 Personnel

In addition to persons supported directly by this contract (indicated by asterisks below), we also list the scientific collaborators who contributed to the published work under this contract.

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 E. P. Keath  
 S. M. Krimigis  
 \*D. G. Mitchell  
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European Space Agency/ESTEC

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NASA/Ames Research Center

### 3.3 Activities

In addition to presenting contributed papers on the subjects listed in Section 3.1 to every Fall and Spring National Meeting of the American Geophysical Union, during the period of the contract, we also participated in the following topical conferences and workshops directly related to our prediction effort

1. Skylab Workshops on Coronal Holes (Boulder, Colorado), 1975-1976.
2. International Symposium on Solar-Terrestrial Physics (Boulder, Colorado), 1976.
3. COSPAR/Study of Travelling Interplanetary Phenomena (Tel Aviv, Israel), 1977.
4. Fifteenth International Cosmic Ray Conference (Plovdiv, Bulgaria), 1977.
5. NATO/AGARD Symposium: "Operational Modelling of the Aerospace Propagation Environment" (Ottawa, Canada), 1978.
6. Solar Probe Science Workshop (Pasadena, California), 1978.
7. Helios/IMP/Voyager Workshop (Lanham, Maryland), 1978.

8. Chapman Conference: "Quantitative Modeling of Magnetospheric Processes" (LaJolla, California), 1978.
9. International Solar-Terrestrial Predictions Workshop (Boulder, Colorado), 1979.
10. Sixteenth International Cosmic Ray Conference (Kyoto, Japan), 1979.

#### 4. SUB-CONTRACT TO MCMATH-HULBERT OBSERVATORY

Professor Helen W. Dodson Prince, Miss E. Ruth Hedeman and Professor Orren C. Mohler continued their on-going analysis of solar-terrestrial relationships under a sub-contract initiated June 1978 and completed September 1979. The objective was to extend their catalog and analysis of solar associations for energetic particle events and geomagnetic storms into the post-maximum years of Solar Cycle 20. For this purpose, 1-10 MeV proton data from the NOAA/JHU detector on IMP-6 was provided, and the solar associations were compared graphically with the particle flux history in an ingenious development of the Solar Activity Charts mentioned in Section 2.6. A sample chart is presented in Figure 1. Time increases horizontally across the chart, and solar longitude is plotted vertically in the lower panel. The track of "families" of recurrent series of active regions therefore runs nearly horizontally across the chart, along with symbols indicating activity while on the visible disc.

Solar particle associations for 1971-1973 and geomagnetic disturbances 1958-1959 and 1969 were analyzed in the following reports, for which we are planning future publication. Date of submission is indicated in parentheses.

|   |              |
|---|--------------|
| Solar Phenomena Associated with the Onsets of Geomagnetic Storms in 1969                | (Sept. 1978) |
| Comments on Solar Associations and Energetic Particle Events in 1971                    | (Nov. 1978)  |
| Solar Phenomena Associated with the Onsets of Geomagnetic Storms in 1958                | (Dec. 1978)  |
| Comments on Solar Associations and Energetic Particle Events in 1972                    | (Jan. 1979)  |
| Comments on Geomagnetic Disturbances in 1959  | (Mar. 1979)  |
| Solar and Geophysical Associations with the Principal Energetic Particle Events of 1973 | (May 1979)   |

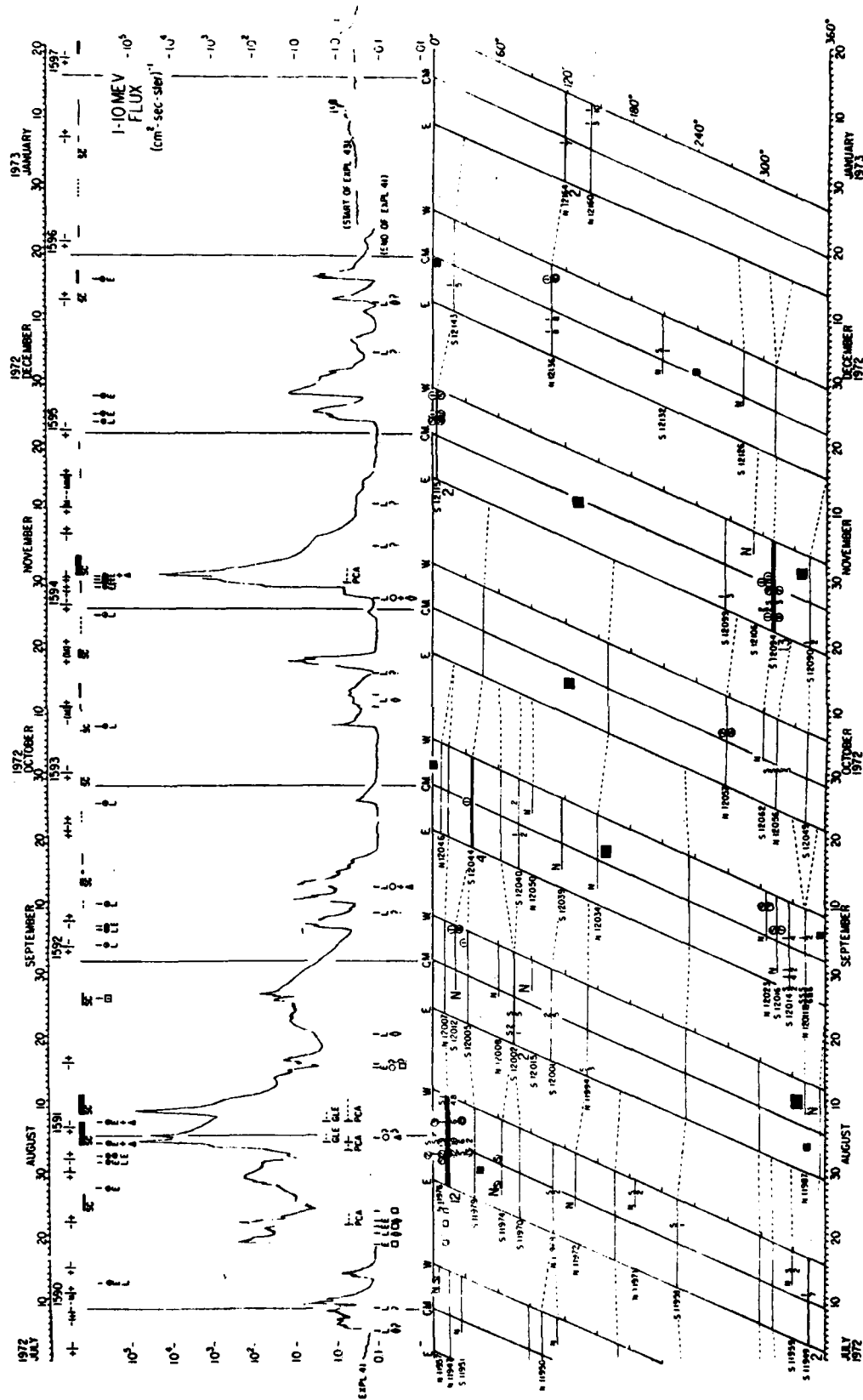


FIGURE 1. Solar-Terrestrial Activity Chart prepared by McMath-Hulbert Observatory. Upper Panel: 1-10 MeV proton flux, solar particle event identifications, geomagnetic activity and interplanetary magnetic field polarity. Lower Panel: Heliographic longitude vs time with histories and inter-relationships of solar active regions; solid squares are sudden disappearances of H<sub>q</sub> filaments.

Comments on Solar Activity and Energetic Particle (July 1979)  
Events in 1973

Principal Geomagnetic Storms in 1970

(Aug. 1979)

## 5. FINDINGS AND RECOMMENDATIONS

The following summary of the status of prediction techniques for solar flare particle events was prepared by E. C. Roelof for Working Group B3 (G. A. Paulikas, Chairman) of the International Solar-Terrestrial Predictions Workshop (Boulder, Colorado, April 1979) and an edited version will appear in the Proceedings. It serves as an appropriate summary for the status of techniques developed under this contract.

### 5.1 Warnings and Reaction-Mode Predictions for Solar Flare Particles

The short term warning mode - forecasting of the particle fluxes which may arrive at the earth from a flare before the flare occurs - requires the prediction of the gross optical, radio and x-ray emission characteristics of the flare. A lumped parameter, such as the "comprehensive flare index" (CFI) of Dodson and Hedeman (1971) might be used for a rather rough estimate of peak flux as well as the total  $> 10$  MeV proton flux and relativistic electron fluxes in cases where coronal and interplanetary propagation are expected to be about average. If predictions of the probability of flare occurrences (e.g., in terms of the distribution of the CFI) can be made for the entire transit of an active region, or for several solar rotations, then rough estimates of energetic particle fluxes could be attempted in the same way for a long-term warning mode; however, "problem" disturbances with anomalously low prediction indices will occasionally occur (Dodson et al., 1979). For predictions of particle fluences or other gross parameters describing solar particles over a complete solar cycle the best course would be to use retrospective data compilations covering the last two solar cycles (Modisette et al., 1965; King, 1974; Stassinopoulos and King, 1972) to estimate the likely course of particle emissions during future solar cycles.

The short-term reaction mode - forecasting the subsequent history of a particle event after the flare has occurred - reduces many of the ambiguities of the warning mode by estimating from real-time data:

- (i) Particle energy spectrum and composition at the acceleration site
- (ii) Spatial and temporal dependence of particle emission from the corona
- (iii) Propagation from the corona to earth

We analyze these three elements of the short-term reaction mode in detail below, and then point out how some of the techniques can be applied to improving the short-term warning mode. The reader should note that a program called PPS-76, developed by Smart and Shea (1979) and described elsewhere in these Proceedings is in operational use and already incorporates some of the ideas which are suggested as requiring further development below. The present discussion builds on the experience and insight gained from developing and using PPS-76.

## 5.2 Spectrum and Composition

Currently the most reliable predictor of  $> 10$  MeV proton fluxes (e.g., PCA events) is the flare radio burst spectral distribution at millimeter and centimeter wavelengths (Castelli and Guidice, 1976; Akin'yan et al., 1977a, 1979a, 1979b; Bezrchenkova et al., 1977). The predictions of proton intensities have been improved by incorporating rough parameters describing coronal propagation. The slope of the proton spectra can also be predicted with reasonable accuracy from radio observations (Bakshi and Barron, 1971a,b; Barron and Bakshi, 1979). There have been few attempts to predict the intensities and spectra of relativistic electrons since the relativistic electrons usually accompany protons  $> 10$  MeV and their spectra are rather reproducible ( $\frac{dN}{dE} \propto E^{-3}$ ). The prediction of relativistic ground level events (GLE) from flare diagnostics is less reliable than for subrelativistic energies.

Composition at high energies (e.g., the proton/helium ratio) is not too variable in large events, but the recently discovered low-energy ( $\sim 1$  MeV/nucleon) "Z-rich" events (Hovestadt et al., 1975; Anglin et al., 1977; Zwickl et al., 1978) are usually from small flares on the sun's western hemisphere and are consequently difficult to predict.

The use of satellite measurements of soft x-ray fluxes ( $\sim 1-10$  Å) for prediction have not been exploited to the extent that the radio observations have. However, the significant contribution of x-ray related indicators to the mix of parameters in the comprehensive flare index (CFI) of Dodson and Hedeman (1971) suggests that the soft x-ray signature may be a good candidate as an additional parameter which may improve our abilities to characterize the acceleration processes occurring in flares.



### Recommendations

- (i) Multi-frequency radio patrols (24-hour coverage) should be continued and the data fed to forecasters for the purpose of improving reaction mode prediction of flare proton intensities and spectra.
- (ii) Satellite measurements of soft ( $\sim 1-10 \text{ \AA}$ ) solar x-rays should continue, and there should be further scientific investigation of the use of both soft and hard x-rays as proton and electron prediction parameters.
- (iii) Optical flare patrols (24-hour coverage) should be continued as these still provide the basic alert for possible flare particle events.

### 5.3 Coronal Particle Emission

#### Findings

Although we do not know whether particle accumulation into coronal storage is impulsive or extended in duration, we do know from satellite and ground-based measurements of particle flux anisotropies that  $> 10 \text{ MeV}$  protons and  $> 0.2 \text{ MeV}$  electrons have been continuously released for as long as a day after a large flare (Roelof and Krimigis, 1977). There is no known solar diagnostic of extended injection; the information regarding extended injection is inferred indirectly from the large outward field-aligned anisotropies of the particles observed in interplanetary space.

Once injected into the corona, high energy particles can cover virtually all longitudes in the corona, and the emission of protons and ions from the corona can be extremely heterogeneous. In the two largest flare proton events in the last solar cycle, multiple spacecraft observations using near-earth and Pioneer detectors revealed intensity differences in  $> 10 \text{ MeV}$  protons of more than a factor of 100 across  $> 50^\circ$  in longitude a day or more after the flare (Keath, et al., 1971; Roelof et al., 1974). Coronal magnetic structure must hold the key to this behavior. A coarse diagnostic of global coronal structure is the  $H_\alpha$  Synoptic Chart (McIntosh, 1972; 1979) which delineates large-scale magnetic polarity boundaries, and has been applied with some success to particle event prediction (Gold and Roelof, 1976; Roelof et al., 1977; Akin'yan and Chertok, 1977; Akin'yan et al., 1977b). More detailed associations of coronal magnetic structures with particle transport have

been made using potential-field calculations based on high resolution Kitt Peak magnetograms (Levine, 1977), but the most direct identifications are possible from emission loops visible in the soft x-ray (44-54 Å) and EUV images obtained from Skylab and various rocket shots (Hanson and Roelof, 1978; Roelof, 1979).

Although not yet fully scientifically validated, it appears that the non-homogeneous transport could result from the requirements that there be closed loops to move the accelerated particles across the corona, but that these particles must eventually find regions of predominantly open field lines in order to escape into the interplanetary medium. These open regions then would be the structures that modulate particle injection into interplanetary space as a function of solar longitude and latitude.

#### Recommendations

- (i) Acquire one image per day of the sun in soft x-rays ( $\sim 40$  Å) or EUV with  $\approx 5''$  resolution (sufficient to identify emission loops  $\approx 0.2R_{\odot}$  above the photosphere). White light coronagraph images are considerably less useful because they do not directly define structures on the disk without extensive and ambiguous deconvolution.
- (ii) Continue daily coverage of the sun with high resolution full disk magnetograms.
- (iii) Develop daily "update" calculations of potential-field magnetic structure over limited or entire photosphere (the latter requiring the previous 27 days of observations for one global computation).
- (iv) Continue scientific analysis of coronal particle transport. Paragraphs (i-iii) of this recommendation can be implemented to provide operationally useful data to forecasters.

#### 5.4 Interplanetary Propagation

##### Findings

During the rising phase of most flare particle events, the flux of particles is anisotropic and field-aligned, indicating that particles faithfully follow (moving) interplanetary field lines (Roelof, 1979); this lack of cross-field scattering should also hold in the decay phase of the event (after coronal

injection is essentially over), when the particles are being "convected" out of the inner heliosphere by the moving field lines (Zwickl and Roelof, 1979). Once the event maximum has been properly identified, the decay phase can be modeled rather accurately, as long as the field lines at earth have sampled a relatively homogeneous coronal injection history. This is often not the case because of strong injection gradients in the corona, so there may be abrupt rises or drops during the decay phase. There are also abrupt changes during the rise phase because our interplanetary field connection to the corona traverses the transition between regions with vastly different emission rates. Changes in the coronal connection cause the principal distortion in solar event histories.

Since the solar wind velocity structure controls the evolution of the large scale interplanetary field, it is fortunate that knowledge of the instantaneous solar wind velocity allows us to estimate the coronal connection point of the field line through the spacecraft at that time (Nolte and Roelof, 1973a,b). Real-time solar wind measurements therefore allow prediction (in the reaction mode) of abrupt discontinuities in particle fluxes (Roelof and Gold, 1978). On the other hand, estimates of evolving solar wind structure would allow a warning mode prediction of abrupt flux changes. Such estimates could come from images of coronal structure (if the modulation is caused by a co-rotating stream) or estimates of the arrival of flare-generated plasma disturbances (which require theoretical calculations that realistically model the three-dimensional distortions of the interplanetary field).

The most promising, immediately available "remote sensing" techniques for the solar wind is the interplanetary scintillation (IPS) of galactic and extragalactic radio sources of small angular diameter (Watanabe, 1979). The main limitation of currently operating IPS arrays is the relatively small number of reliably scintillating sources ( $< 10$ ) at observing frequencies  $> 70$  MHz. Only a few of these sources lie in the ecliptic plane, so directional sensitivity to approaching solar wind disturbances has a seasonal dependence. Nonetheless, IPS measurements during some months provide unique and valuable information for warning mode predictions of strong distortions in particle event histories.

### Recommendations

- (i) Solar wind speed should be provided in real time for prediction of particle event histories in the reaction mode. The paper of Tsurutani and Baker (1979) in these Proceedings describes steps presently being taken to implement this recommendation.
- (ii) Interplanetary scintillation multi-site observations of solar wind speed should be obtained on a daily basis. Even though IPS directional sensitivity is seasonal, measurements during the optimal periods of the year are extremely valuable for predictions in the warning mode.
- (iii) Research concerning three-dimensional distortion of the interplanetary field by solar flare plasma disturbances is essential to the understanding necessary for predicting the effect of these disturbances on energetic particle event histories.

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